DISTILLATE FUEL PROCESSING FOR MARINE FUEL CELL APPLICATIONS

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Abstract

FuelCell Energy, Inc. (FCE) is developing a 625 kW fuel cell power plant for marine applications based on its Direct Carbonate Fuel Cell (DFC™) technology. The power plant is designed for operation on Mil-F-16884J Naval distillate fuel designated as NATO F-76. This fuel is characterized as a 385°C (max) end boiling point diesel fuel with up to 1% sulfur by weight. The development is part of the U.S. Navy 2500 kW Ship Service Fuel Cell Program, sponsored by the Office of Naval Research and administered by the Naval Surface Warfare Center Carderock Division.

The technical approach is based on adapting FCE's commercial Direct Fuel Cell technology for marine applications. This fuel cell system utilizes a mixture of alkali metal carbonates as the electrolyte and operates at 1100-1250°F where internal reformation of hydrocarbon fuels is feasible. Because the process waste heat is captured by the endothermic fuel reforming reaction, the DFC™ stack provides unsurpassed overall power plant efficiency.

Processing of this distillate fuel in the marine power plant design includes a high-pressure hydrodesulfurizing first stage producing desulfurized liquid fuel. The second stage employs an adiabatic prereformer, which reacts the desulfurized distillate with steam producing a methane rich fuel gas. The converted fuel is expanded through a turbo generator, reheated and directed to the anodes in the DFC™ stacks. The methane is then converted to hydrogen in the DFC™ stacks which in turn is electrochemically converted to water, thereby producing DC power. Water for steam is recovered from fuel cell exhaust making the process self-sufficient in its water needs.

Tests on sample batches of NATO F-76 supplied by the U.S. Navy have confirmed the processes of desulfurizing and adiabatic prereforming. Subscale tests of the hydrodesulfurizing process have reduced sulfur levels in the fuel to less than 100 ppb. Tests on the adiabatic prereforming stage have confirmed stable composition of the converted fuel. A 10-cell stack of FuelCell Energy's commercial nine square foot active-area has operated for over 1,000 hours to date producing power from the converted NATO F-76 distillate fuel, validating the fuel processor design.

Introduction

In 1997 the Office of Naval Research (ONR) initiated a three-phase advanced development program to demonstrate that commercially developed fuel cell technology can meet ship service power requirements for surface combatants. The initial phase of the ship service fuel cell (SSFC) program was focused on conceptual design and critical component testing. Phase 2 of the program includes detailed design, construction, and land-based testing of a 0.5 MW demonstration power plant by FuelCell Energy at its facility in Danbury, CT. The demonstration power plant will be delivered to the Naval Surface Warfare Center's Test Center in Philadelphia, PA in 2003 for additional land-based performance testing. Phase 3 of the program includes testing of the power plant at sea.

DFC technology is unique in that it can operate directly on hydrocarbon fuels without the use of an external reformer. The approach to processing of the NATO F-76 marine distillate fuel is based on desulfurization followed by adiabatic prereforming to a methane-rich gas which can be reformed internally by the fuel cell. This approach minimizes changes to the fuel cell power plant being developed by FCE for commercial applications.

Under an earlier DoD-sponsored project, FCE tested fuel processing systems for fuel cell applications using DF-2 and JP-8. Table 1 compares the properties of JP-8, DF-2 and NATO F-76. The marine distillate NATO F-76 is slightly heavier than DF-2 in terms of molecular weight and specific gravity. It also has the highest maximum sulfur level.

Table 1
PROPERTIES OF LOGISTIC FUELS JP-8, DF-2 AND NATO F-76

PROPERTY	JP-8	DF-2	NATO F-76
Molecular Formula (avg)	$C_{11.5}H_{22.8}$	$C_{14.6}H_{26.3}$	$C_{14\text{-}8}H_{26.9}$
Molecular Weight	161	202	205
H/C Ratio (Molar)	1.98	1.80	1.82
Sulfur Mass, %	0.3 (max)	0.5 (max)	1.0 (max)
Specific Gravity	.809	.849	.852
Net Heating Value, Btu/lb	18,570	18,442	18,358
Net Heating Value, Btu/gal	125,038	130,340	130,235

In order to use a distillate fuel in a fuel cell power plant it must be processed to convert it to a fuel useable by the fuel cell. For a low temperature fuel cell, this means sulfur removal, conversion to H_2, and conversion of CO to CO_2. For a high temperature fuel cell this means sulfur removal and conversion to H_2. Since the carbonate fuel cell stack operates at temperatures sufficiently high for internal steam reforming, it is capable of internally reforming methane to produce the needed anode hydrogen. This means that the fuel processor need only convert the NATO F-76 fuel to methane rather than hydrogen. This feature provides the carbonate fuel cell system with a major advantage over lower temperature fuel cell systems because the conversion of NATO F-76 to methane can be carried out adiabatically thereby maximizing the efficiency of the fuel processor. Figure 1 below depicts the entire fuel cell power plant with fuel processing of NATO F-76.

Sulfur removal

Both prereforming catalysts and fuel cells require sulfur levels in fuels to be below 0.1 ppm. Although worldwide standards are gradually lowering sulfur levels in transportation fuels, it will be necessary to have sulfur removal steps in fuel cell power plants. Deep desulfurization can be achieved by hydrodesulfurization (HDS). Testing at FCE with NATO F-76 distillate fuel containing 3800 ppm sulfur has demonstrated the capability to achieve 0.1 ppm sulfur with this process. Regenerable sulfur capture downstream of the HDS is being tested to minimize maintenance, size and weight of the equipment. Two regeneration cycles have been completed to date with good results as testing continues. The sorbent regeneration is carried out by using simulated fuel cell cathode exhaust which is partially depleted in oxygen.

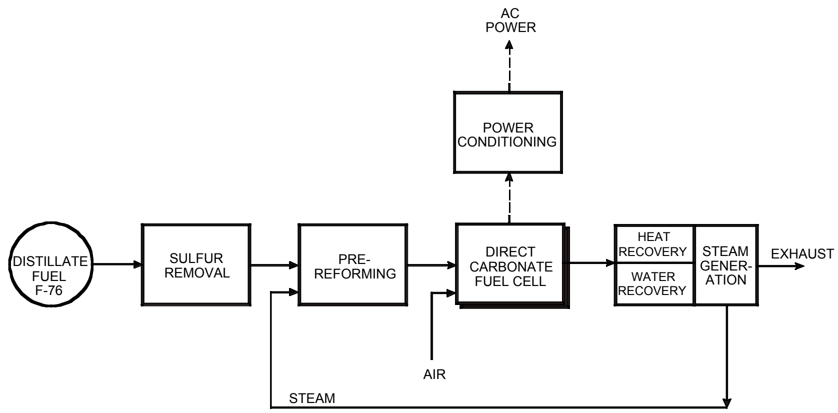

Figure 1
BLOCK DIAGRAM OF FUEL CELL POWER PLANT OPERATING ON NATO F-76
NATO F-76 naval distillate is converted to fuel gas by desulfurization and adiabatic prereforming

Prereforming

Adiabatic prereforming of desulfurized NATO F-76 is being used to convert the naval distillate to a methane-rich gas useable by the fuel cell. As shown by the reactions below, the endothermic reforming reaction is driven by the exothermic shift and methanation reactions, thereby eliminating the need to provide heat to the reactor.

(1)	Reforming	$C_nH_m + nH_2O \rightarrow nCO + (n+m/2)\ H_2$	Endothermic
(2)	Shift	$CO + H_2O \rightarrow CO_2 + H_2$	Exothermic
(3)	Methanation	$CO + 3H_2 \rightarrow CH_4 + H_2O$	Exothermic

Testing at FCE for over 1400 hours of operation indicates that complete conversion of the naval distillate is achieved with no higher hydrocarbons above C_1 detected. The gas composition of the fuel gas produced is close to the expected equilibrium composition as shown in Table 2 below. A subscale carbonate fuel cell stack built with 9 ft^2 cells has operated on prereformed NATO F-76 for over 1,000 hours with stable performance.

Power plant process description

The nominal power plant design rating is 625 kW. A simplified process flow diagram is shown in Figure 2. Two stacks of direct carbonate fuel cells in series provide 445-600 VDC to the power conditioning system which converts the DC to 60 Hz AC power at 450 volts. In the first stage of fuel processing, the NATO F-76 fuel is mixed with recycled hydrogen and small amount of make-up hydrogen. The mix stream is hydrodesulfurized at elevated pressure. The stream then passes into a bed with ZnO where the H_2S reacts with ZnO forming ZnS. The stream leaving the ZnO absorber bed is cooled, the desulfurized F-76 fuel is condensed, and the hydrogen is recirculated. The ZnS produced is regenerated to ZnO in situ using depleted air from the fuel cells.

In the second stage of fuel processing, the desulfurized fuel is mixed with steam, heated and flows to an adiabatic prereformer. The adiabatic prereformer produces a methane-rich fuel stream.

Table 2
PREREFORMER EXIT GAS COMPOSITION
Measured values are close to equilibrium

	Calculated Equilibrium (Volume %)	Measured (Volume %)
H_2	24.3	23.4
CH_4	51.7	51.8
CO_2	23.4	24.2
CO	0.6	0.6
Total	100	100

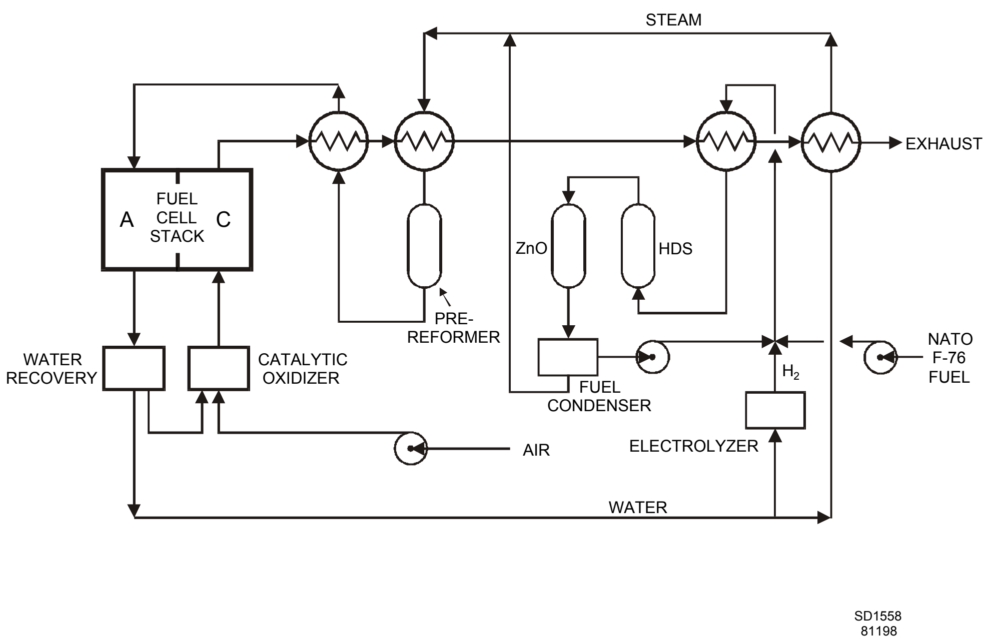

Figure 2
SHIP SERVICE FUEL CELL POWER PLANT SIMPLIFIED PROCESS FLOW DIAGRAM
Fuel processing and fuel cell are thermally integrated for high efficiency

The converted fuel is let down in pressure through a turbo expander generator producing about 50 kW of AC power. The methane-rich fuel is reheated and flows to the anodes in the DFC™ cells producing DC power. Water produced in the cells is recovered by condensation, and raised to steam using waste heat from the fuel cells. Sufficient water is recovered so that the process is self sufficient in its water needs.

Power plant configuration and performance

The equipment in the power plant is arranged as shown in Figure 3. Fuel processing beds are located with maintenance access for periodic catalyst replacement at 1-2 year intervals. The LHV efficiency of the ship service fuel cell (SSFC) power plant is compared to a high-speed diesel generator set and a gas turbine generator set in Figure 4. The high efficiency of the SSFC over its entire power range has significant advantages in marine applications where the ship service load varies widely during anchoring in port and cruising at sea. The high efficiency achieved is due to the high efficiency of the fuel processor in converting naval distillate to fuel gas and the fuel cell's high efficiency in converting fuel gas to power.

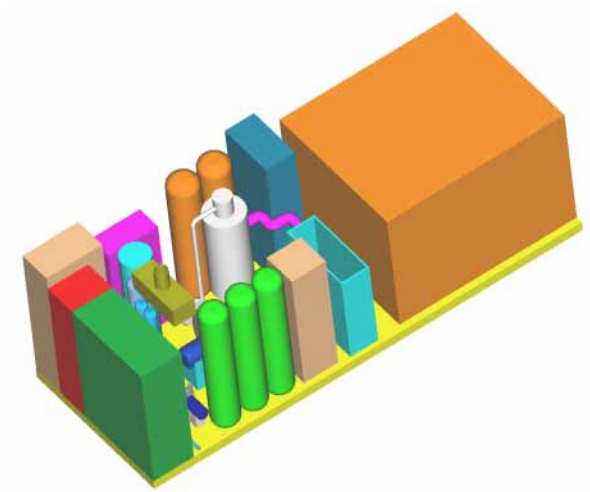

Figure 3
625 kW POWER PLANT EQUIPMENT ARRANGEMENT
Fuel processing units are located with access for maintenance

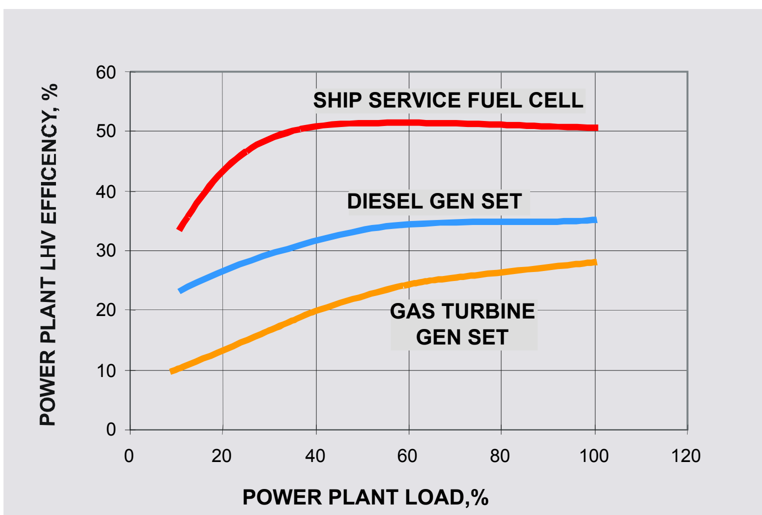

Figure 4
SHIP SERVICE FUEL CELL POWER PLANT EFFICIENCY
Efficiency is significantly higher than generation alternatives over the entire load range

Conclusions

Processing of naval distillate NATO F-76 can be achieved efficiently for the internally reforming carbonate fuel cell, thereby making this fuel compatible with the DFC™ for marine fuel cell power applications. A fuel cell power plant for marine applications based on FuelCell Energy's DFC™ technology promises significant fuel saving advantages over power generation alternatives due to its high efficiency. The development of a 625 kW power plant for the U.S. Navy using NATO F-76 distillate fuel is underway and will be tested in 2002.

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